Spinning Up Tracers in the Ocean

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Statement of Problem

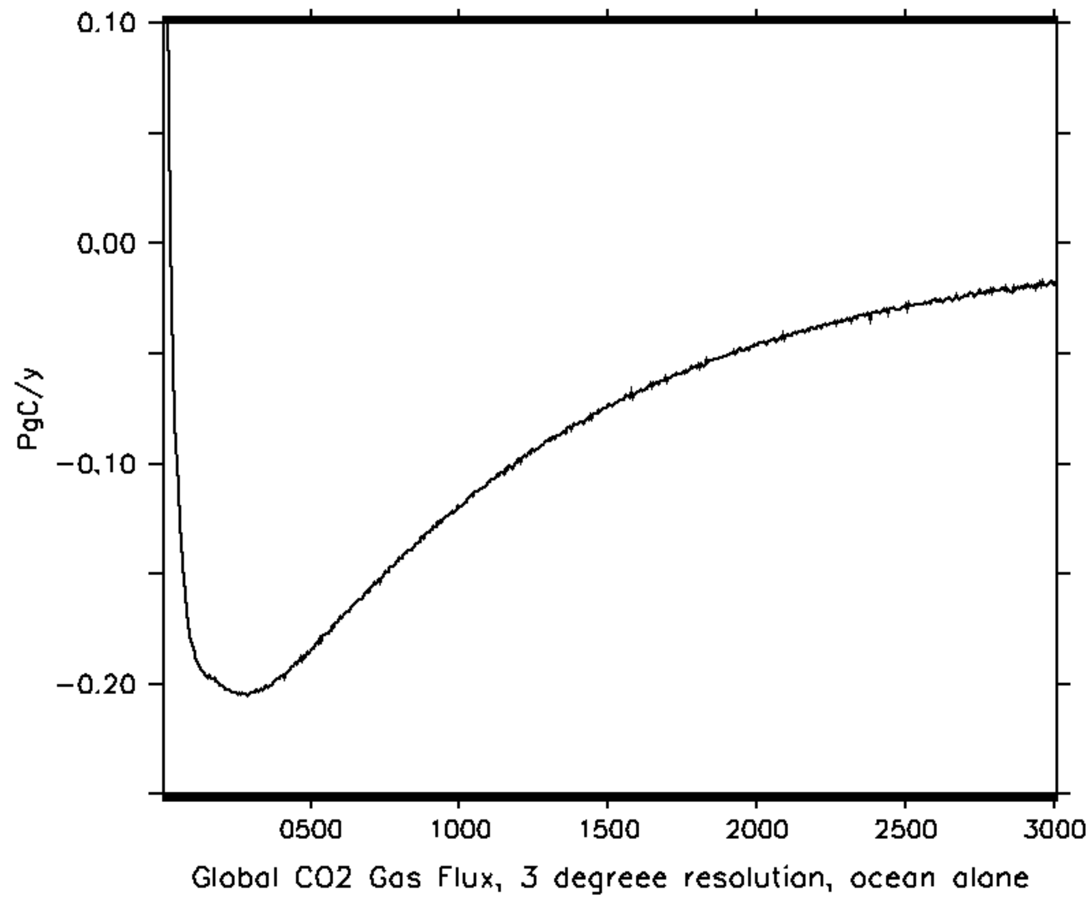
- Generate tracer distributions that are in balance with respect to (non-stationary) ocean model circulation (advection and mixing).
  - More precise statement later
- Applications:
  - Initializing transient experiments
  - Compare modeled tracers to observations
  - Optimize parameters to reduce model bias
    - Requires ability to spinup repeatedly

Target Model Configurations

- x1 grid: 320x384x60 (~4.2×10^6 grid points)
- Tracer modules
  - Abiotic radiocarbon: 2 tracers
  - CESM 1.2 ecosystem: 27 tracers
- Daily surface forcing w/ interannual variability
  - CORE or coupled model forcing
- Parameterized diurnal cycle for shortwave
  - Precludes taking large time steps for ecosystem

Direct Integration

BGC tracers in the ocean, such as dissolved inorganic carbon, take thousands of years to equilibriate when run directly forward in time. Running 3000 years at 25 model years per wall clock day takes ~4 months. It is not feasible to do this repeatedly.



Newton-Krylov Solvers

Li & Primeau (2008) , Khatiwala (2008)

- Let u(t) denote tracer state.
- Model Map: $u(t) = \Phi(u(0),t)$
- Φ incorporates advection, mixing, BGC, etc.

- Solve $\Phi(u_0,T)=u_0$ for u_0.
  - T is period of forcing and circulation.

- Rewrite: $F(u) \equiv \Phi(u,T)-u=0$.
- Newton's Method:

$$u_{k+1} = u_k - (\partial F/\partial u)^{-1} * F(u_k)$$

Newton-Krylov Solvers

Li & Primeau (2008) , Khatiwala (2008)

- Use Krylov iterative method (GMRES) to solve:

$$(\partial F/\partial u)(\delta u_k)=-F(u_k)$$

- Each GMRES iteration evaluates $(\partial F/\partial u)(\delta u)$
- Finite Difference Approximation
  - $(\partial F/\partial u)(\delta u) \approx (F(u+\sigma\delta u)-F(u))/\sigma$
  - Note this is a forward model run of length T.

- Preconditioner is a MUST for GMRES

$$(P^{-1}(\partial F/\partial u))(\delta u_k)=(P^{-1})(-F(u_k)),\ P\approx(\partial F/\partial u)$$

Preconditioner Approach

Li & Primeau (2008) , Khatiwala (2008)

- Approximate forward model over t=0..T with a single backward Euler step with timestep T.
- Assuming this approximation is exact, derive exact formula for (∂F/∂u).
- Inverting resulting approximate (∂F/∂u) requires inverting a 3D sparse matrix (SuperLU)
- Matrix entries are terms of the form ∂(tend)/∂(tracer) for different tracer tendency terms
  - IRF tracer module has been written for POP to obtain these partial derivatives

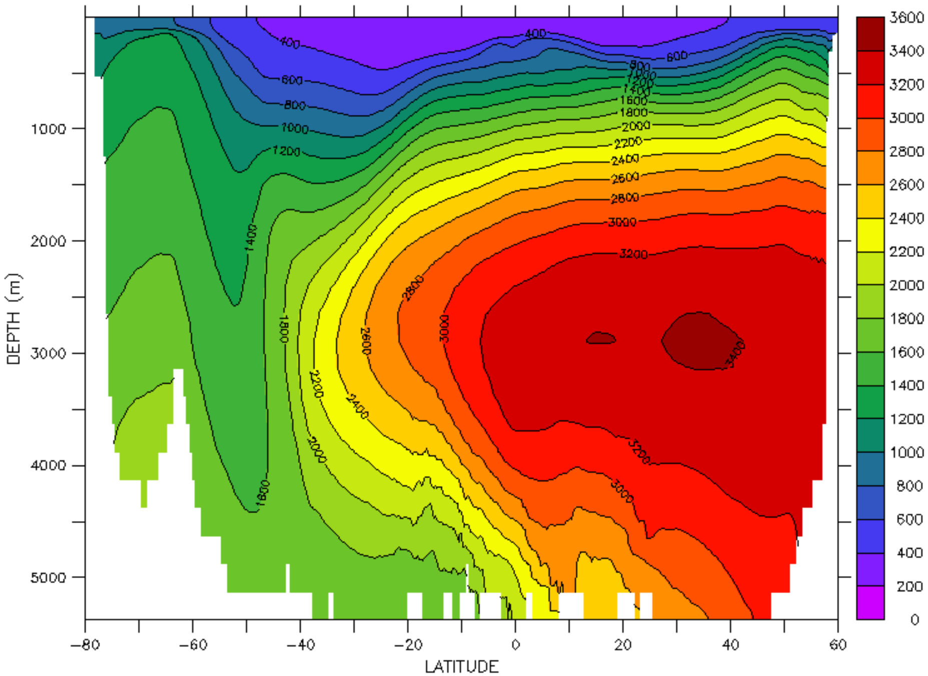
Results for Abiotic Radiocarbon

- Normal Year Forcing, x1 grid
- Physics spun up for 150 years
- OCMIP2 protocols (implementation from A. Jahn)
- Spin up C and ^{14}C wrt model year 0151
  - Natural ^{14}C, no bomb signal
- 4 Krylov Iterations per Newton Iteration

Newton Iteration	Residual RMS change/yr	CO_2 Gas Flux (PgC/yr)	% ocean where drift in $\Delta^{14}C > 10^{-3}$ ‰/yr
0	0.796	-4.025	100% (IC for $\Delta^{14}C = 0$)
1	0.205	-0.242	70.6%
2	0.026	-0.007	13.3%
3	0.004	-0.001	2.6%

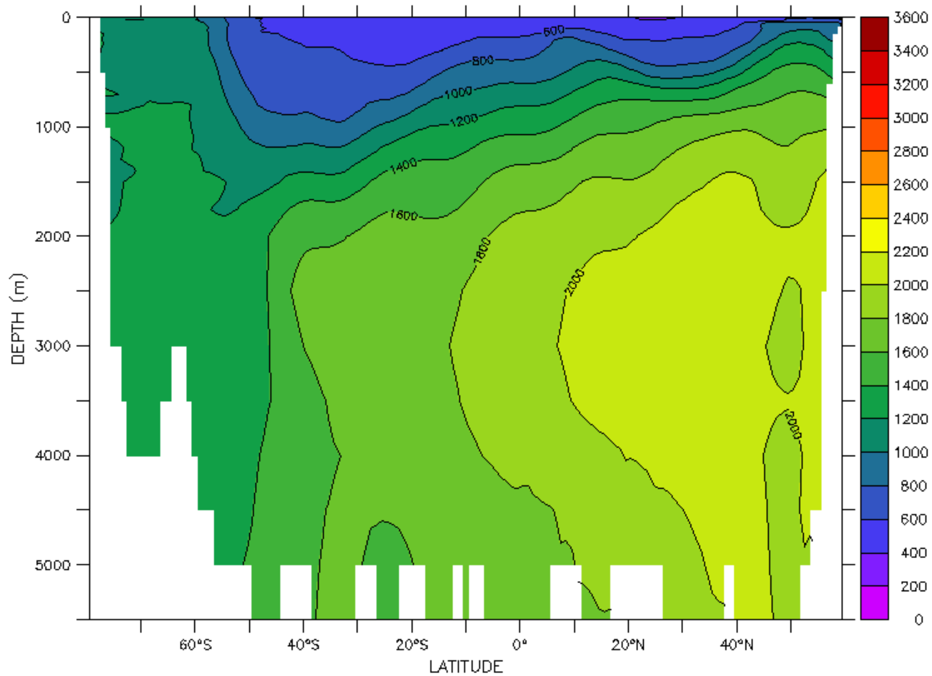
Comparing Results to GLODAP

Standard Model $\Delta^{14}C$ Age



14C Age, Standard Model, 190<LON<210

GLODAP $\Delta^{14}C$ Age

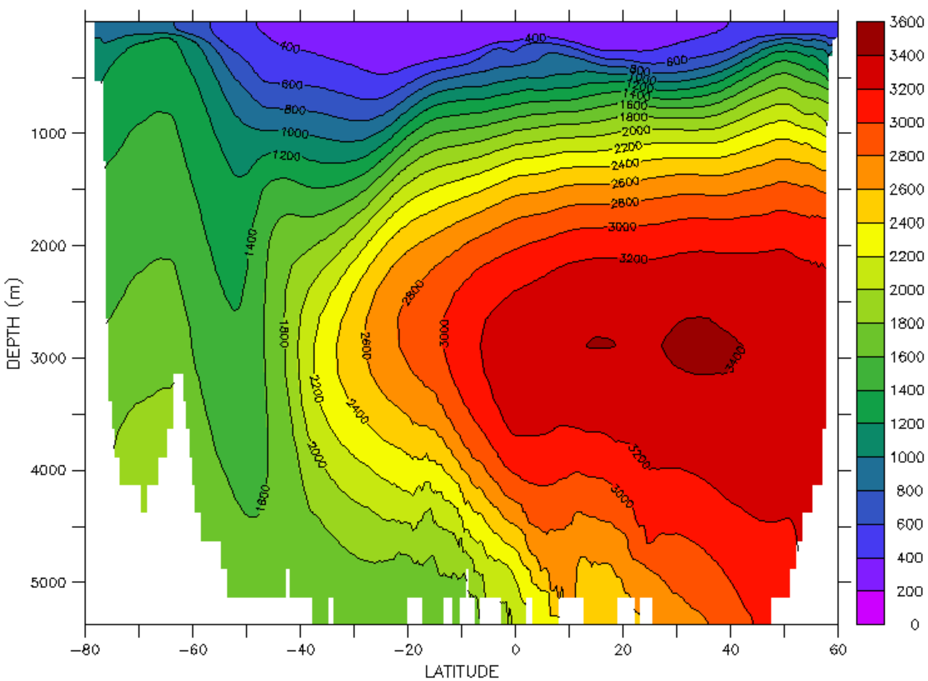


14C Age, GLODAP, 190<LON<210

Impact of GM change on Radiocarbon

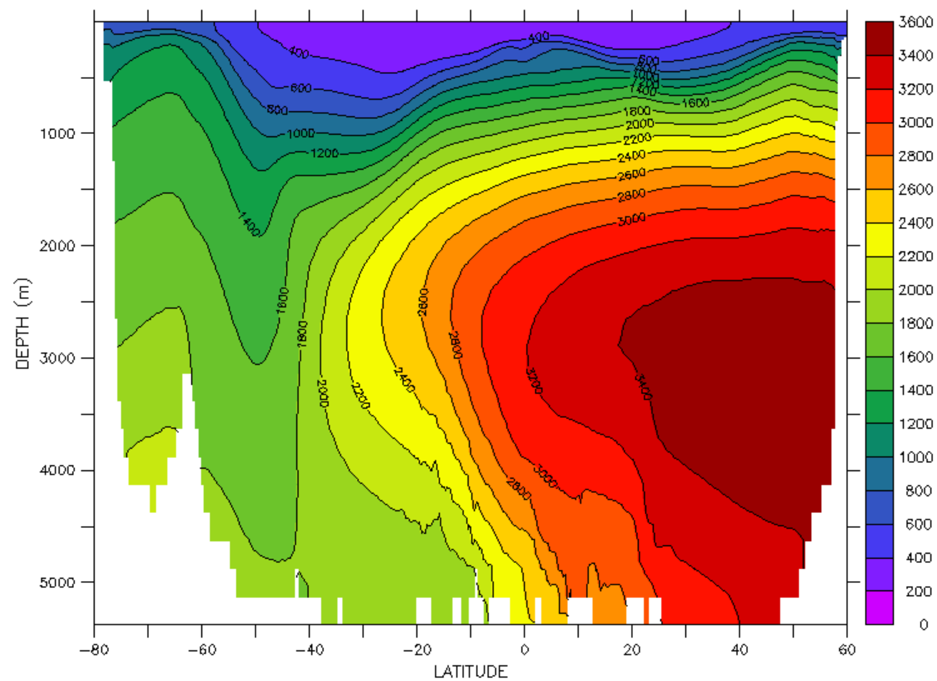
100 year physics spinup done from end of spinup of standard model

Standard Model $\Delta^{14}C$ Age



14C Age, Standard Model, 190<LON<210

Modified GM $\Delta^{14}C$ Age



14C Age, Modified GM, 190<LON<210

Application to Full BGC Model

(work in progress)

- Apply Krylov solver to slow tracers only, using fixed productivity fields.
- Implementation is to create a shadow copy of each slow tracer and apply perturbations of Krylov iterations to the copy.
- Replace original slow tracers w/ shadow copy after Krylov solve and run a few years to allow fast tracers to adjust, recomputing productivity fields.
- Subtlety: source-sink terms for duplicate tracers, loss of nutrient-productivity feedbacks is non-physical.

Measures of Convergence

(old results, CCSM3.5, x3 grid)

Direct Integration

Model Years	CO_2 Gas Flux (PgC/y)
500	0.1477
1000	0.0964
1500	0.0636
2000	0.0404
2500	0.0269
3000	0.0181

Newton-Krylov
4 iterations+5 adjustment years per Newton step

Newton Iteration	RMS Tracer Change per year	CO_2 Gas Flux (PgC/y)
0	0.11486	0.1240
1	0.09034	0.1658
2	0.06261	0.2131
3	0.03683	0.2821
4	0.02593	0.1596
5	0.02295	0.1333
6	0.01297	0.0805
7	0.01050	0.0717
8	0.00750	0.0446

Summary & Ongoing Work

- NK spinup for ^{14}C w/ NY Forcing, x1 grid works
  - Useful diagnostic of ocean ventilation
- Full BGC spinup work is ongoing
  - Previous results w/ shadow tracers show promise
  - Shadow tracer implementation nearly complete for CESM 1.2 BGC module
  - More results will be shown @ Ocean Sciences poster
- Incorporate interannually varying forcing
- Q: How long does physics need to be spun up?
- Q: Can technique be extended to T & S?
  - Try shadow variable approach